What do GCM parameterizations of aerosol forcing of climate change need from observational and process studies?

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PNNL

- Plan of talk
  - What do GCM modelers “know”?
  - What do we know we don’t know?
  - How might we make progress?

With thanks to Steve Ghan, Xiaohong Liu, Cecile Hannay, Rich Neale, Sungsu Park, Chris Bretherton, Hugh Morrison, Andrew Gettelman, Jennifer Comstock, Dan Cziczo, Rahul Zaveri

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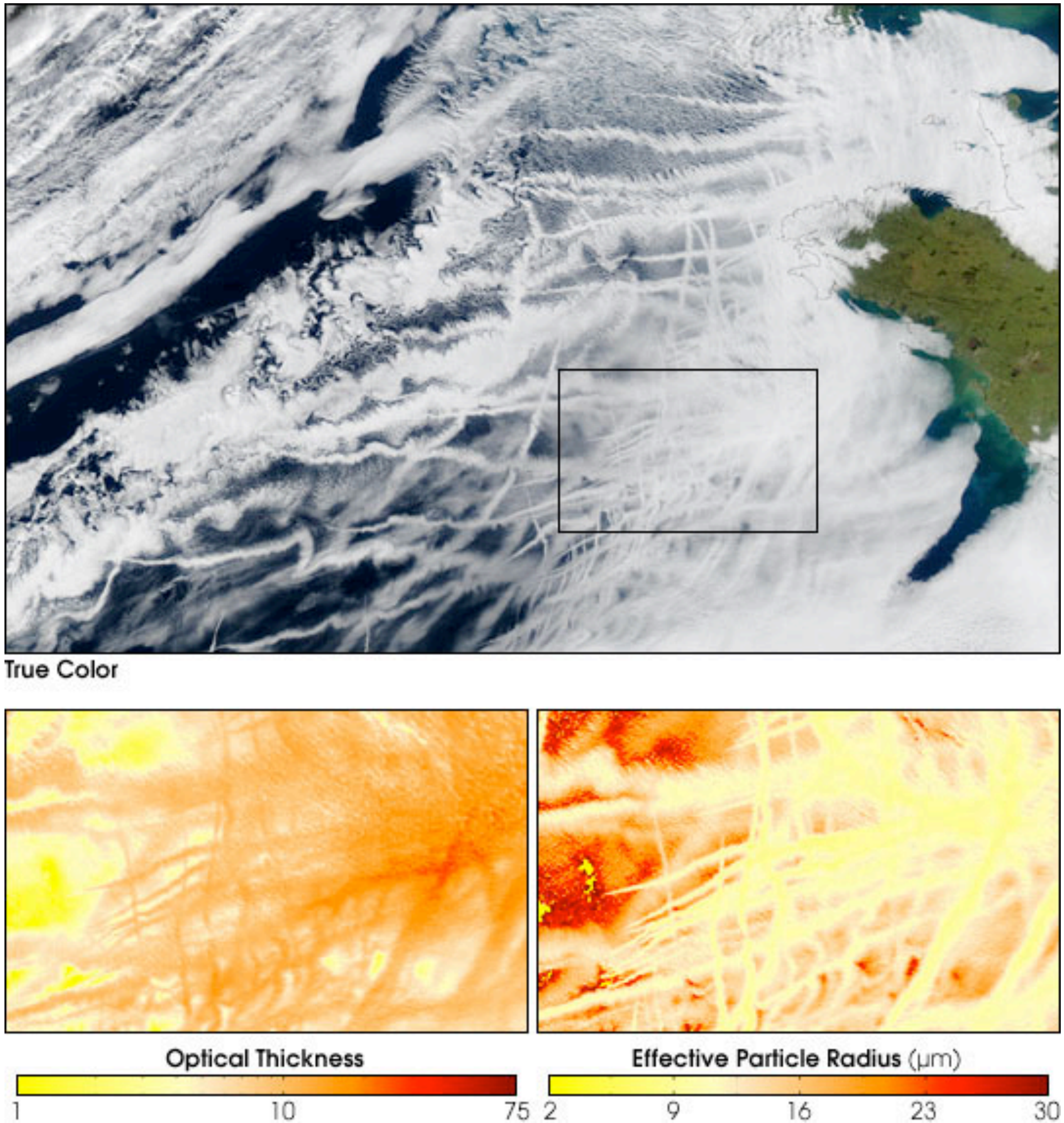
Setting the stage:

- Aerosols are obviously important to climate
  - They attenuate and scatter light - acting to heat and cool the atmosphere - but also modulating the delivery of light to the surface, influencing for example, ecosystems
  - They provide sites for cloud condensation
  - They provide sites for and participate in photochemistry
  - They provide transport paths for chemical components and nutrients that would not otherwise exist in nature
- GCMs use them for all these things!
- Title of talk involves aerosol forcing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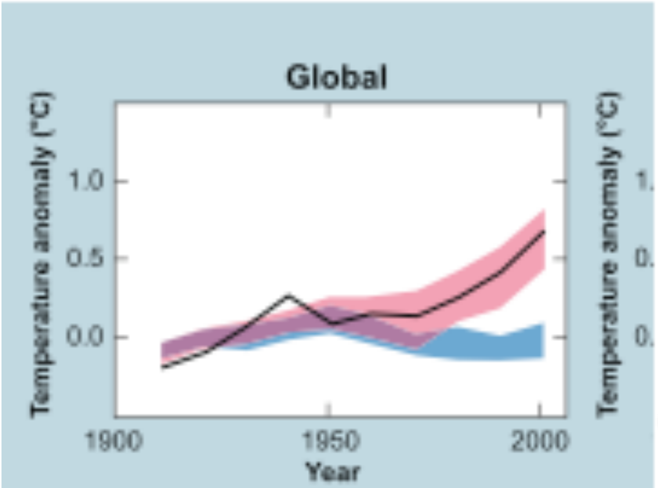
30

Why do we care?

- Many models reproduce the historical trend in T_S when "total" anthropogenic forcings were included
- Some models didn't include aerosol cloud interactions (the "indirect effect")
- Models "forcings" differ by > a factor of 2
- Models "climate sensitivities" differ by > a factor of 2



IPCC, AR4

Kiehl, GRL, 2007

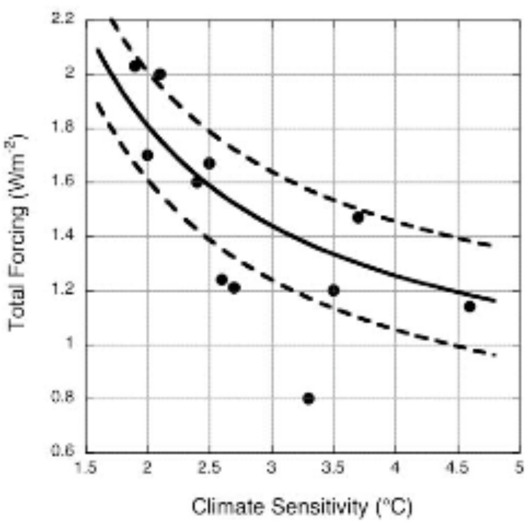


Figure 1. Total Anthropogenic Forcing (Wm^{-2}) versus equilibrium climate sensitivity (°C) from nine coupled climate models and two energy balance models that were used to simulate the climate of the 20th century. Solid line is theoretical relationship from equation (4). Dashed lines arise from assuming a ±0.2 Wm^{-2} uncertainty in ocean energy storage in equation (4).

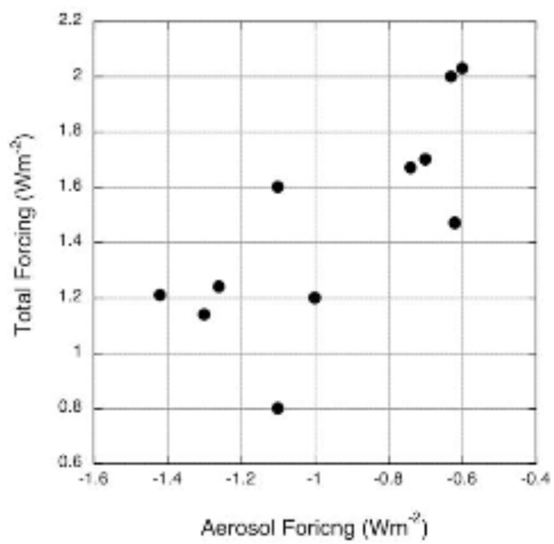
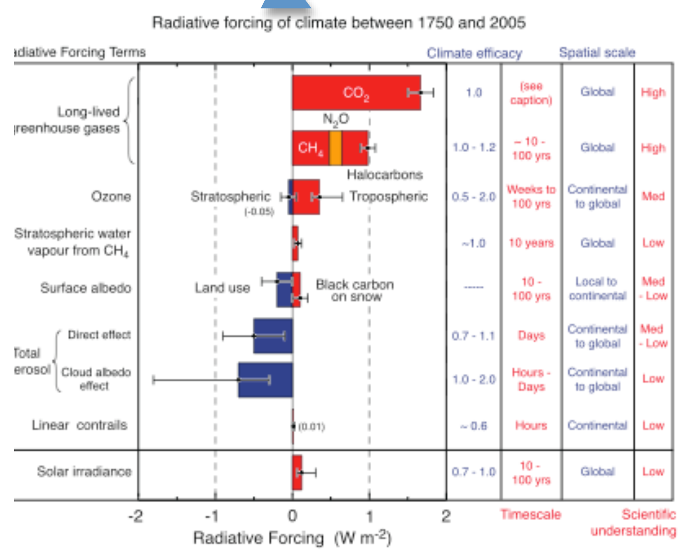


Figure 2. Total anthropogenic forcing (Wm^{-2}) versus aerosol forcing (Wm^{-2}) from nine fully coupled climate models and two energy balance models used to simulate the 20th century.



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Consensus (IPCC, AR4, Chapt 7) Aerosol Cloud effects

Table 7.10a. *Overview of the different aerosol indirect effects and their sign of the net radiative flux change at the top of the atmosphere (TOA).*

Effect	Cloud Types Affected	Process	Sign of Change in TOA Radiation	Potential Magnitude	Scientific Understanding
Cloud albedo effect	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	Negative	Medium	Low
Cloud lifetime effect	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby presumably prolonging cloud lifetime	Negative	Medium	Very low
Semi-direct effect	All clouds	Absorption of solar radiation by absorbing aerosols affects static stability and the surface energy budget, and may lead to an evaporation of cloud particles	Positive or negative	Small	Very low
Glaciation indirect effect	Mixed-phase clouds	An increase in IN increases the precipitation efficiency	Positive	Medium	Very low
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing super-cooled clouds to extend to colder temperatures	Positive or negative	Medium	Very low

Table 7.10b. *Overview of the different aerosol indirect effects and their implications for the global mean net shortwave radiation at the surface, F_{sfc} (Columns 2-4) and for precipitation (Columns 5-7).*

Effect	Sign of Change in F_{sfc}	Potential Magnitude	Scientific Understanding	Sign of Change in Precipitation	Potential Magnitude	Scientific Understanding
Cloud albedo effect	Negative	Medium	Low	n.a.	n.a.	n.a.
Cloud lifetime effect	Negative	Medium	Very low	Negative	Small	Very low
Semi-direct effect	Negative	Large	Very low	Negative	Large	Very low
Glaciation indirect effect	Positive	Medium	Very low	Positive	Medium	Very low
Thermodynamic effect	Positive or negative	Medium	Very low	Positive or negative	Medium	Very low

What have we learned during & since the AR4?

- How complicated aerosol cloud interactions are
- Most GCMs are attempting to include all the effects mentioned in previous slide
- Where agreement was “fortuitous” before, now the global temperature record has become a ‘necessary test’ for GCMs
- Too many degrees of freedom (multiple unknowns, one observable)
- What are we leaving out?
- How might we constrain the system more strongly?

Readying ourselves for AR5

- "Approximate Indirect effect" estimated by:
  - Keeping GHGs fixed
  - SSTs fixed
  - Changing emissions of aerosols from preindustrial emissions to present day
  - Assessing change in
    - Clear sky fluxes
    - Change in cloud radiative forcing resulting from changes to cloud drop number (CDNC) in turn depending on aerosols
- The "dirty laundry"
  - True for our model and many, many others
  - Many places (latitude, longitude, altitude) have quite low CDNC
    - Highly susceptible to changing aerosols
    - Poor characterization of sources (of aerosols and precursors)?
    - Poor or missing physics?

Estimates of direct and indirect forcing from next generation NCAR model. All these runs used same cloud microphysics. Some had different drop activation. Some used different PBL and shallow convection schemes. Some had different aerosol physics (bulk vs modal). All else identical

Drop Activation

Emissions

Turbulence & BL clouds

- Delta (preindustrial – present day)
  - Positive -> cooling, Negative -> Warming
  - Limited = lower bound on CDNC of 20/cm3
  - Units W/m2

Case	Comment	Delta-SWCF	Delta-LWCF	Direct	Net
Modal old-DN	unlimited	+1.2	0.0	+0.6	+1.8
Modal old-DN	limited	+0.6	+0.2	+0.5	+1.1
Modal new-DN	unlimited	+1.9	+0.0	+.6	+2.5
Modal new-DN	limited	+1.4	+0.1	+0.6	+2.1
Modal, new-DN_v2	Unlimited+emis.	+0.4	+0.2	+0.5	+1.4
Config 2b(u37)	Limited	+2.3	-0.9	+0.3	+1.6
Config 3a(u33)	Unlimited	+3.2	-1.0	+0.4	+2.7
Config 3b(u34)	limited	+2.8	-0.8	+0.3	+2.3

The message

- All these configurations provided a similar picture of the “climate”
- Even one model, worked on by a single team with a goal of producing a consistent physical picture of the processes controlling aerosol forcing can span the range of the IPCC models.
- Low CDNC clouds are places that matter. (How frequently do clouds with < 20/cm3 really occur?)

How else might anthropogenic aerosols effect clouds (and climate)?

- Longwave Indirect Effect (Lubin and Vogelman, 2006)
  - Emissivity ~ $1/r_e$, changes in the arctic surface fluxes ~

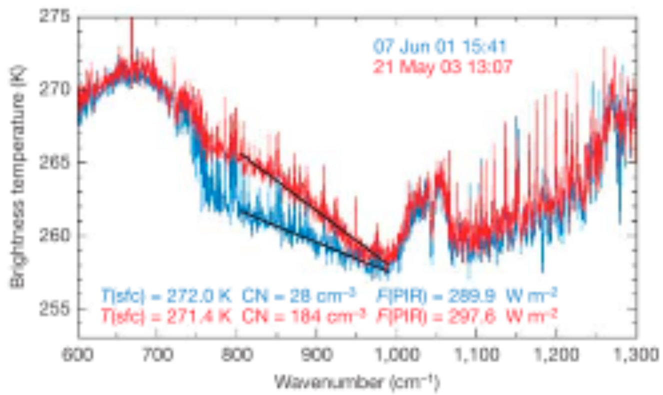


Figure 2 | Examples of AERI measurements. Downwelling emission spectra measured by the NSA AERI beneath two clouds with very different condensation nuclei (CN) concentrations. Near-surface (2 m) air temperature T(sfc) and pyrgeometer-measured downwelling longwave flux F(PIR) are also indicated.

- Precipitation
  - ACPC activity (ILEAPS, IGAC, GEWEX)

Treatments of heterogeneous vs homogeneous nucleation

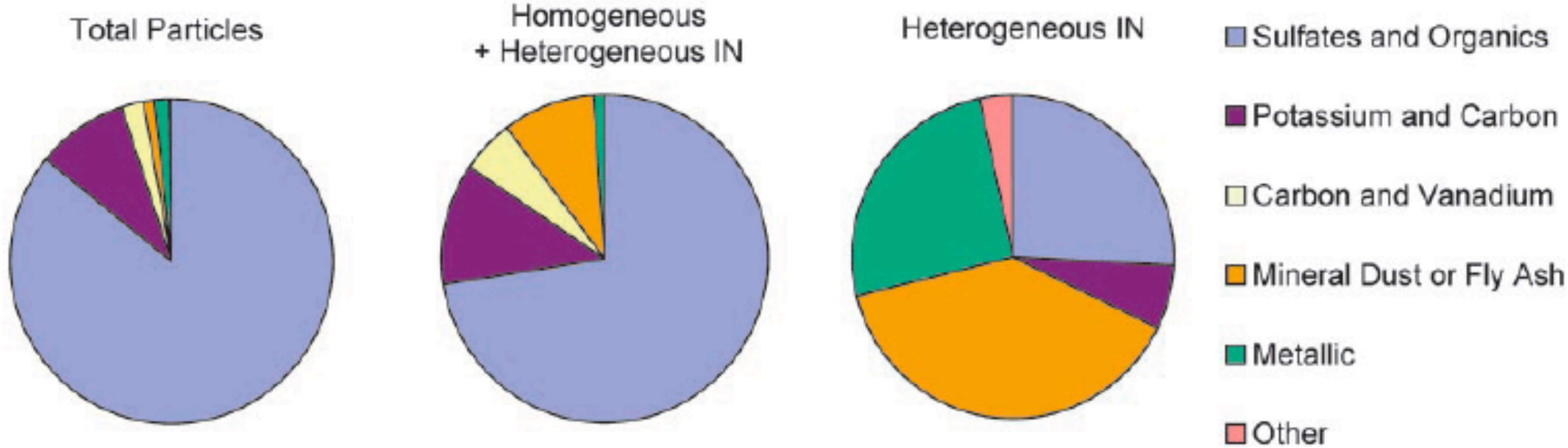


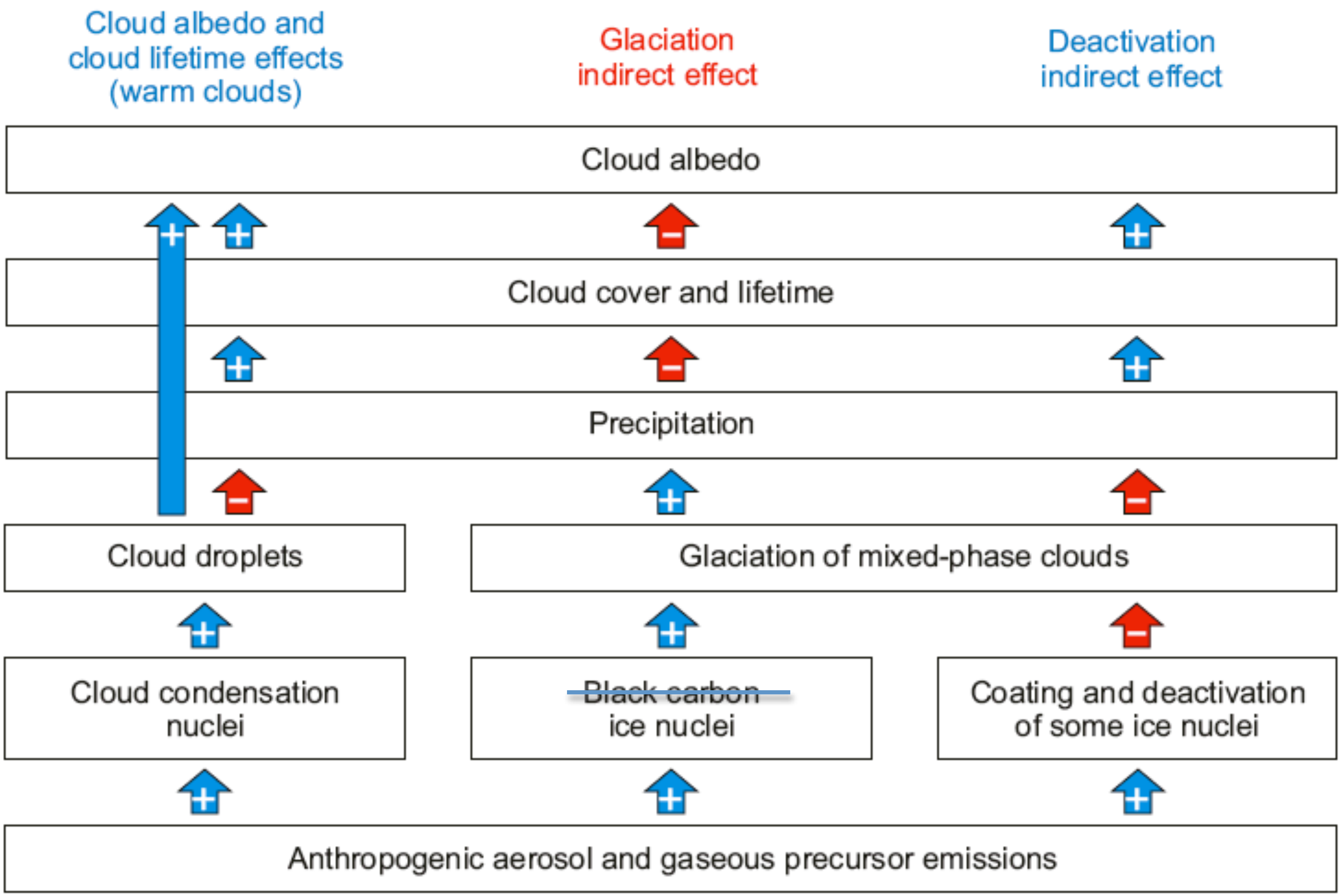
Fig. 4. Statistics of different particle populations based on cluster analysis of PALMS mass spectra. The total aerosol composition is shown (*Left*), and the composition of nucleated ice-crystal residuals are shown in the regime under which homogeneous freezing was dominating heterogeneous nucleation (*Center*) and under conditions favorable only to heterogeneous nucleation (*Right*).

Demott et al, PNAS, 2008

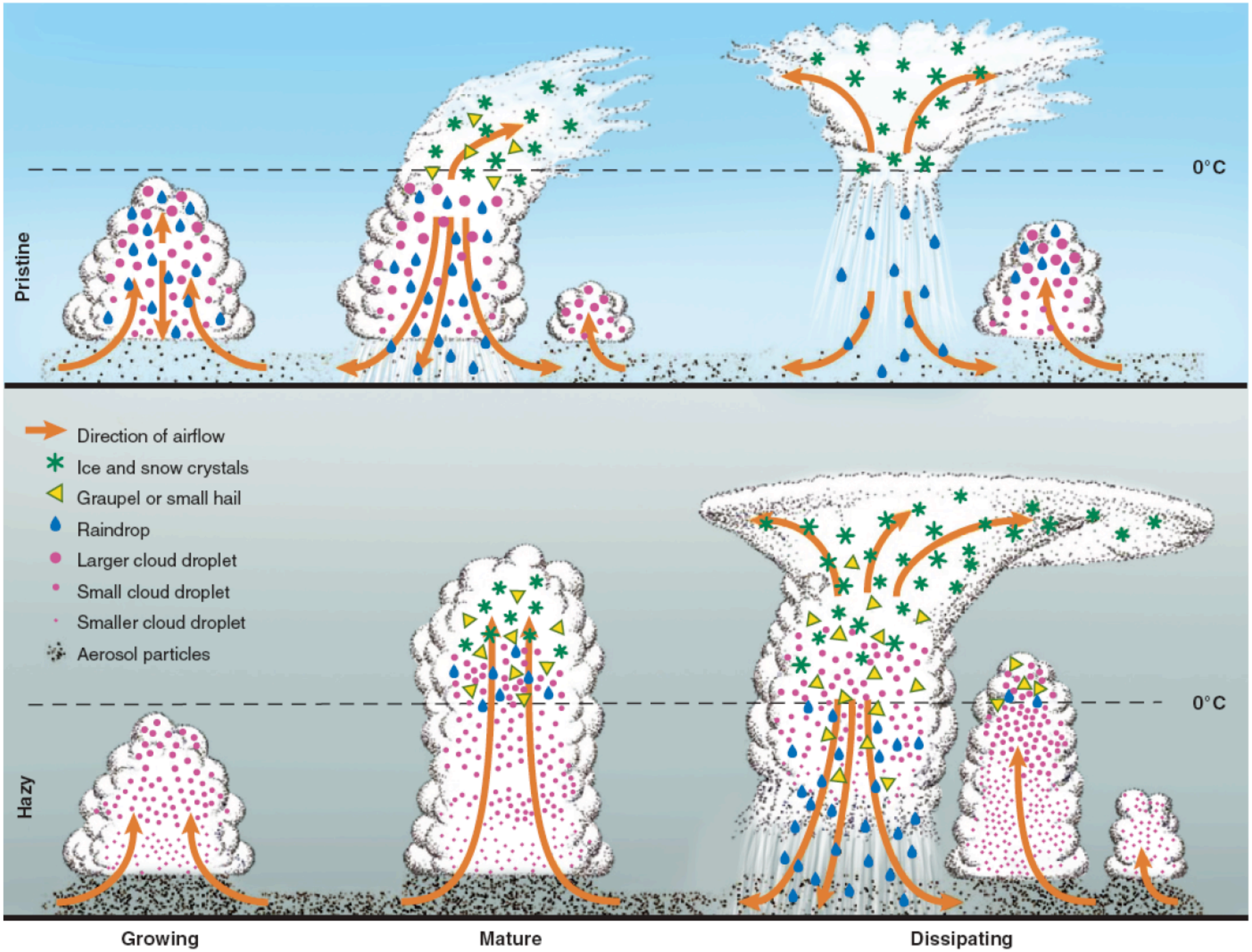
14658 | www.pnas.org/cgi/doi/10.1073/pnas.2532677100 DeMott *et al.*

- Some studies treated soot as an effective ice nuclei. Recent work suggests that it is not
- Importance of metals
- Impedance of nucleation by presence of sulfate and organics
- Role of dust/soil from biomass burning, agriculture, etc

Nucleation vs Deactivation (Lohmann and Hoose, 2008)

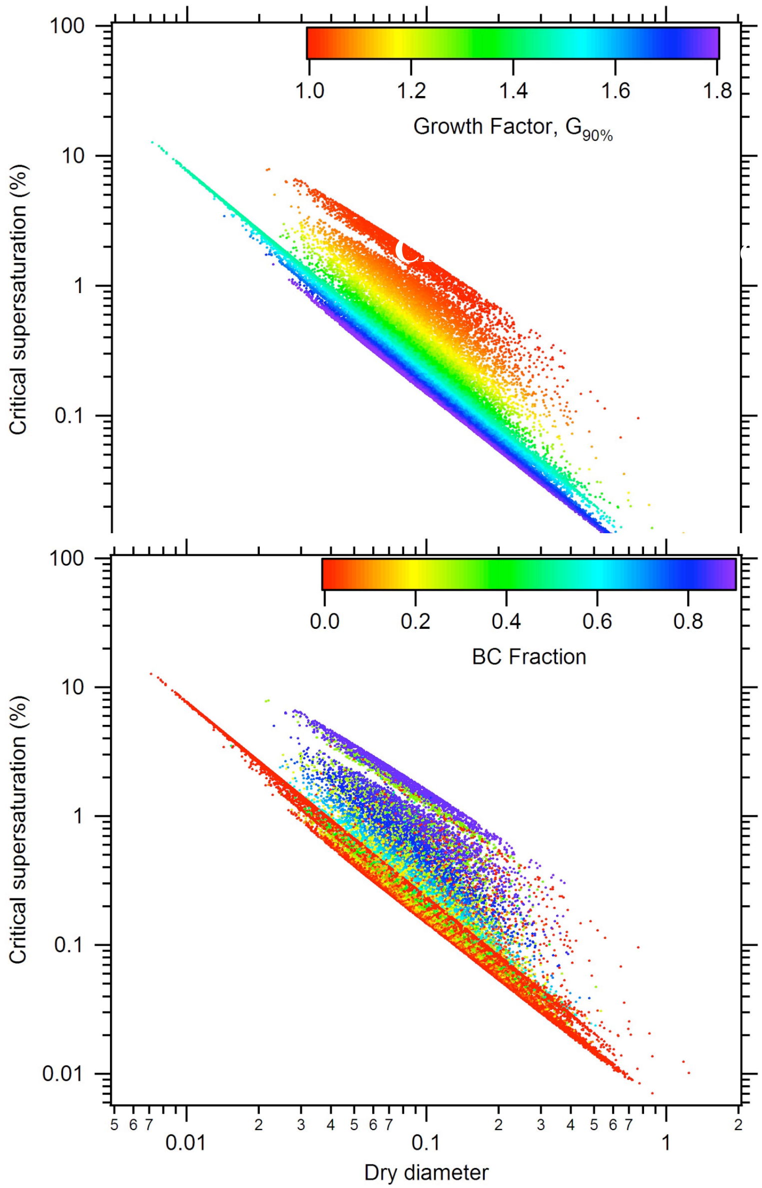


Role of CCN/IN on convection (Rosenfeld, 2008)



Complications with 2nd AEI

- Boundary layer clouds don't always follow classic hypothesis
- Guo, 2007
  "Our results show the neither the cloud fraction nor the cloud liquid water path necessarily increase with increases in aerosols" (depends on subsidence rate). "second AIE may enhance or reduce first AIE"
- (similar conclusions in Zuidema et al, 2008, and earlier work by Ackerman, Feingold, and others)
  - Depend on pollution levels, cloud dynamics, large scale dynamics
  - Most pristine not necessarily most susceptible
- Many of the subtleties of the processes controlling these features are not easily represented in today's climate models



Role of Aerosol composition on cloud drop evolution?

- Position 1: (Dusek et al, Science, 2006) "Size matters more than chemistry for cloud nucleating ability of aerosol particles"
- Position 2: (Cubison et al, ACP, 2008) "It is shown that a realistic treatment of the state of mixing of the urban aerosol distribution is critical in order to eliminate model bias"… (*describing both prediction of CCN but also cloud drop number.)*
- What is a climate modeler to do?

Zaveri et al, 2009, in prep
Particle resolved modeling study downwind of urban plume

Questions

- Do we understand the fundamental physical phenomena (e.g. the mechanisms responsible for perturbing cloud components)?

  I think we have a good grasp of many/most of the mechanisms responsible for aerosol cloud interactions, and can reproduce many features of those mechanisms in detailed models for short time scales in strongly constrained situations. Yet there are still serious disagreements and lack of consensus at the process level

- Do we understand man's influence by aerosol on an individual cloud or cloud system?

  There are still components we don't understand or cannot characterize by consensus (e.g. role of chemical composition, or ice nucleation)

- Do we understand the role of those perturbations on "climate"?

  Models are tools that represent and integrate our knowledge about a class of phenomena too complex to be assembled and solved in our head. I don't think we yet have a model that captures all that we know. I am not sure we yet have a model that captures enough to be quantitative about anthropogenic aerosol's impact on clouds, and their subsequent role on climate.

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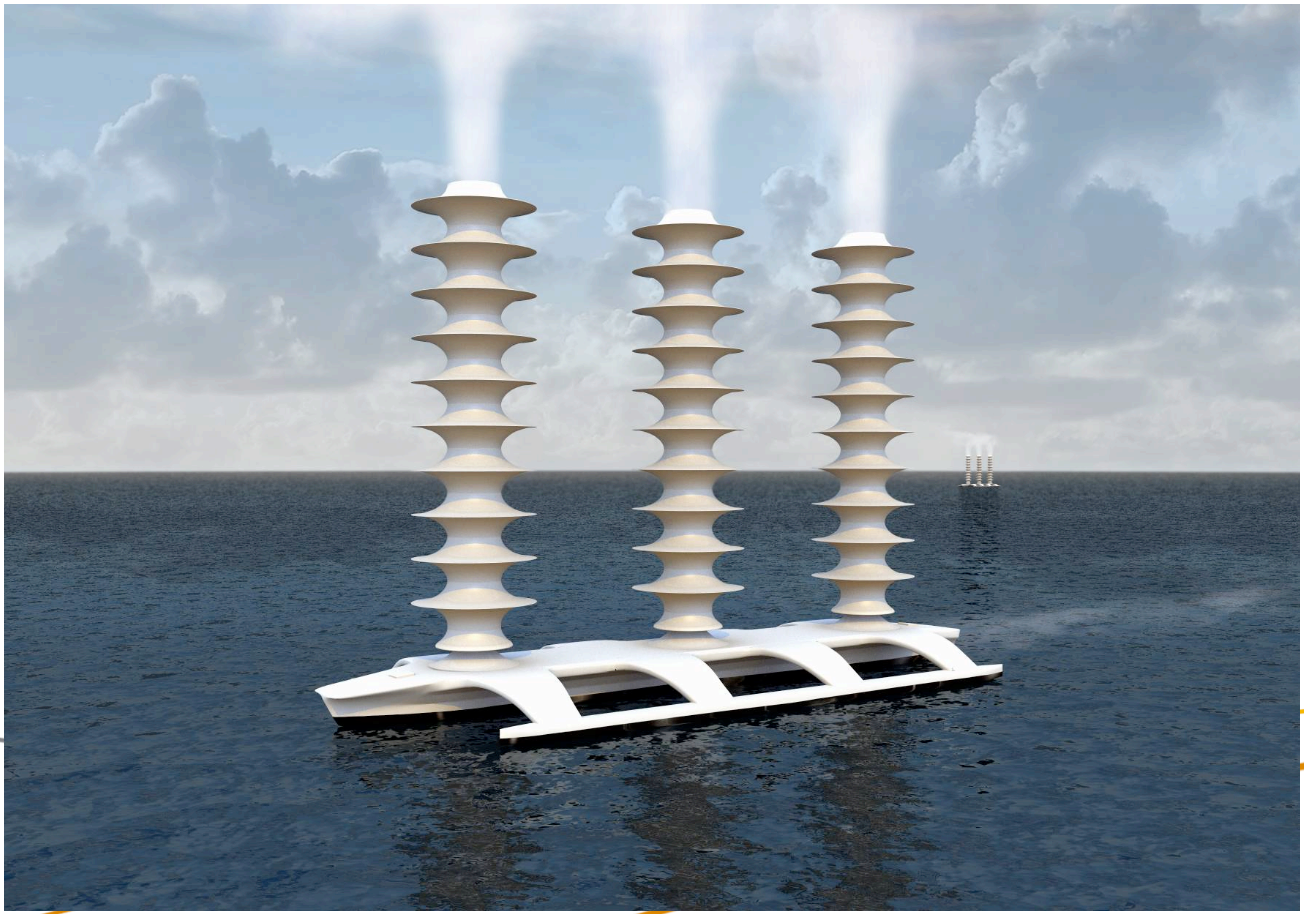
How do we make progress?

- Continuing the ASP/ARM-like activities obviously help
- What about a field experiment to “perturb” the system in a controlled fashion in a regime we think we understand?



Salter et al, 2008

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Variations on a theme of “geoengineering”

- Latham et al, *Global Temperature Stabilization via Controlled Albedo Enhancement of Low-Level Maritime Clouds, 2008,* special issue on geoengineering, Phil. Trans. A.,
- Salter et al, *Sea-going hardware for the cloud albedo method of reversing global warming 2008,* special issue on geoengineering, Phil. Trans. A.,
- Lets ignore geoengineering… Can we design an experiment that really tests our knowledge of aerosol cloud interactions by perturbing the regime?